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SPACE SHUTTLE  
ORBIT MANEUVERING ENGINE  
REUSABLE THRUST CHAMBER PROGRAM

TASK VI DATA DUMP

HOT FUEL ELEMENT INVESTIGATION

(NASA-CR-141677) SPACE SHUTTLE ORBIT  
MANEUVERING ENGINE, REUSABLE THRUST CHAMBER  
PROGRAM. TASK 6: DATA DUMP HOT FUEL  
ELEMENT INVESTIGATION (Rocketdyne) 45 p HC  
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## INTRODUCTION

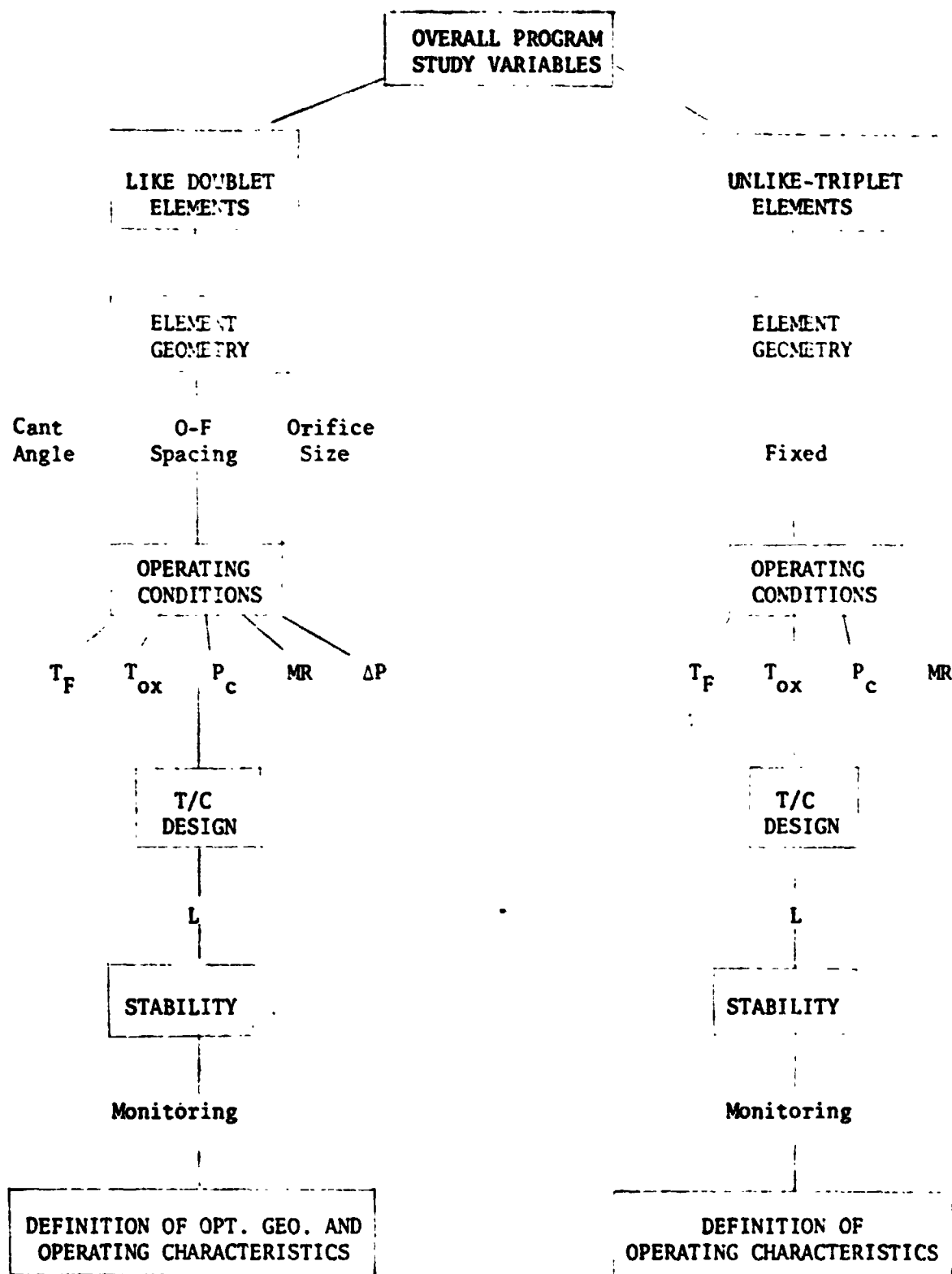
The purpose of this effort was to evaluate, by subscale injector hot-fire tests, injector configurations designed for a regenerative-cooled engine to support the Task XI injector design. The subscale approach has several advantages over using full-scale hardware, for example; (1) subscale hardware provides considerable cost savings, and (2) variations in operating characteristics are magnified making detection easier. The validity of using properly sized subscale hardware to guide the design of full scale injectors has been demonstrated in previous studies. In these studies valuable information has been acquired relating the sensitivity of unlike impinging elements to popping and steady-state blowpart. In particular, under a Company-sponsored program (S.A. 61205) several subscale unlike-doublet and triplet-injector configurations were evaluated to determine the effect of operating conditions and fuel temperature on  $c^*$  performance as well as stability. The results clearly demonstrated that with the NTO/MMH combination optimum injector designs require consideration of reactive stream separation, popping and manifold/combustion interaction. Based upon these findings, the specific objectives of Task VI were to determine (1) the optimum like-doublet element geometry for operation at conditions consistent with a fuel regeneratively-cooled CME (hot fuel, 200-250°F), and (2) the sensitivity of the triplet injector element to hot fuels. The results of this study are presented below.

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## SUMMARY

The objectives of this study were to determine (1) the optimum like-doublet element geometry for operation at conditions consistent with a fuel regeneratively-cooled OME (hot fuel, 200-250°F), and (2) the sensitivity of the triplet injector element to hot fuels. The like-doublet injector was selected as a prime candidate since it is insensitive to popping, and properly designed should also be insensitive to the reactive stream separation phenomenon. The triplet element type appears to offer the greatest potential for operation without experiencing reactive stream separation with hot propellants using an unlike-impinging element type. The program was structured as shown in the schematic of Fig. 1. For the like-doublet element type the element geometry, operating conditions, T/C design and stability were studied. From this rather detailed effort optimum geometry was defined as well as the overall operating characteristics. The triplet element study was less comprehensive since the element geometry was not varied. As a consequence only the operating characteristics could be determined.

For the like-doublet injector, tests were conducted to determine (1) the optimum cant angle and spacing, (2) the minimum number of elements required, (3) the possible turbulent mixing effects as a function of chamber length, (4) the influence of oxidizer temperature on performance characteristics, and (5) the effect of operating conditions on  $c^*$  efficiency (i.e., MR and  $P_c$ ). To meet these objectives a total of 81 tests were conducted at Rocketdyne's Propulsion Research Facility. The results showed that avoidance of



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FIGURE 1. SCOPE OF THE OVERALL PROGRAM EFFORT

reactive stream separation using the like-impinging doublet required selection of cant angle and spacing such that mixing is initiated only after droplet formation occurred. An optimum configuration was determined which was insensitive to fuel temperature. For oxidizer temperatures up to 100°F performance was invariant. It appears that for the designs studied performance is mixing limited.

The triplet element studied showed a decrease in  $c^*$  performance with increasing fuel temperature. Low frequency instability (280 cps) was observed during start-up and sometimes spontaneously during the run. It is thought that this is manifold/combustor coupled and could be solved by incorporation of "dams" in the manifolds.

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## TEST HARDWARE

Some of the test hardware used during this program was available from a Company-sponsored study. However, for completeness, all of the hardware are described herein.

### INJECTOR DESIGNS

#### Like-Doublet Subscale Injector

A total of 11 injector configurations were designed; 10 were fabricated. A summary of the injector design specifications are provided in Table 1. The first injector listed in Table 1 (AP73-223) consists of 3 pairs of elements of the AP73-223 injector simulates the L/D #1 full-scale like-doublet injector (AP72-275) tested on the contract demonstration and Integrated Thrust Chambers. Elements 2, 3, and 4 contain four like-doublet elements and represent a subscale version of the maximum number of elements (286) which can be contained within a 2:1 contraction ratio OME chamber. Three fan impingement angles - 22.5, 34, and 45 degrees - are incorporated in these elements. The 34 degree element closely simulates the L/D #2 injector tested on the NAS9-12524 Contract (Acoustic Cavity Technology). Specifications for both full-scale injectors are contained at the bottom of Table 1. Injectors 5 through 10 are two additional spacings for each impingement angle, 22.5, 34, and 45 degrees. These designs having increased spacing allows the propellant spray additional time to form droplets before mixing. Injector #11 is simply injector #5 with enlarged oxidizer orifices to equalize the oxidizer to fuel momentum. Previous studies suggested that balancing the oxidizer and fuel momentum results in improved mixing characteristics.

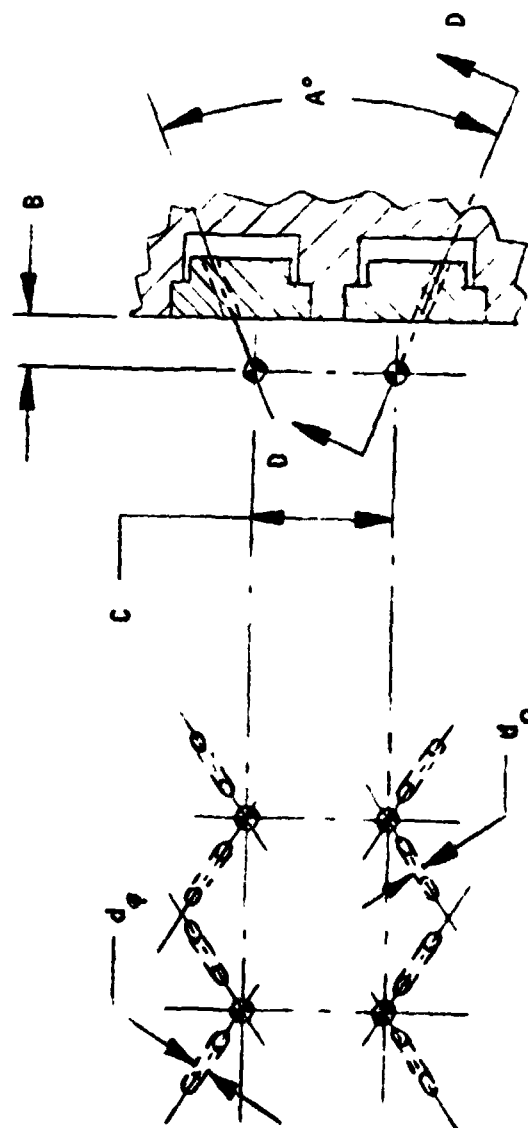


TABLE 1. SUMMARY OF LIKE-DOUBLET INJECTOR DESIGNS

No.	Part Number	$\alpha^0$	$A^0$	B	C	N	$d_f$	$d_o$
1	AP73-223	60	22.5	.188	.188	3	.0289	.0332
2	AP73-224	60	22.5	.150	.178	4	.0243	.0259
3	AP73-225	60	34.0	.150	.146	4	.0243	.0259
4	AP73-226	60	45.0	.150	.114	4	.0243	.0259
5	AP73-532-011	60	45.0	.100	.417	4	.0243	.0259
6	AP73-532-021	60	34.0	.104	.437	4	.0243	.0259
7	AP73-532-031	60	22.5	.107	.458	4	.0243	.0259
8	AP73-532-041	60	45.0	.100	.265	4	.0243	.0259
9	AP73-532-051	60	34.0	.104	.285	4	.0243	.0259
10	AP73-532-061	60	22.5	.107	.306	4	.0243	.0289
11	AP73-532-011A*	60	45.0	.100	.417	4	.0243	.0289
S-1	AP72-275	60	22.5	.188	.187	186	.0300	.0345
S-2	AP72-369	60	34.0	.150	.140	386	.0251	.0263

NOMENCLATURE

- $\alpha^0$  - Impingement angle of pair  
 $A^0$  - Inclination angle of element  
 $B$  - Impingement Height  
 $C$  - Impingement Distance  
 $d_f$  - Fuel Orifice Dia.  
 $d_o$  - Oxidizer Orifice Dia.  
 $N$  - Number Elements



SECTION D-D

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A detailed drawing of the subscale injectors is given in Fig. 2. Note that the manifolds represent segments of typical ring grooves and simulates the full-scale design. The injectors are made from Aluminum 2219T6. The jet impingement angle is 60 degrees for all injectors.

#### Unlike-Triplet Subscale Injector

The triplet injector was fabricated on the Company-sponsored program. A detailed drawing of the injector is provided in Fig. 3. This design consists of 3 elements. The oxidizer and fuel orifice diameters are 0.032 and 0.057-inch, respectively. The included impingement angle is 60 degrees. This design also represents a segmented ring configuration.

#### THRUST CHAMBER

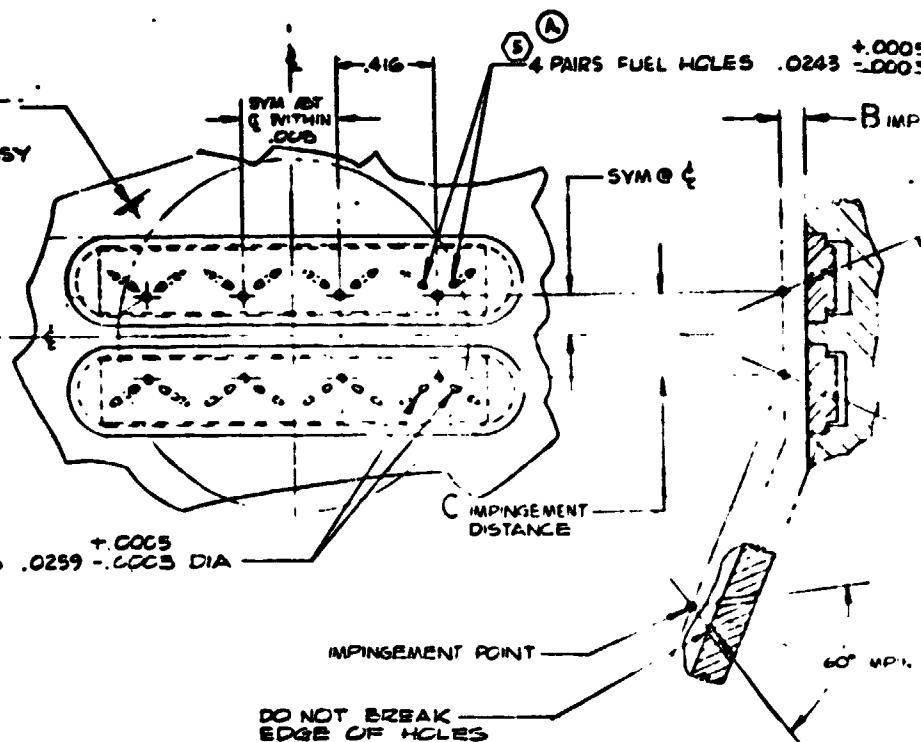
The test hardware consists of a copper workhorse chamber with a 1.5-inch chamber diameter, a throat diameter of 0.62-inch, and a chamber length (injector-to-throat) of 3.9 inch. The combustor has provision for two chamber pressure transducers and one Photocon transducer. A flexatallic seal is used at the injector/chamber interface. This chamber was available from the prior effort. Two additional chamber length spools were fabricated during this program in order to vary L. The lengths are 3 and 6 inches providing a maximum overall length of 13 inches.

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-001 ASSY OF,  
1 EA REQD FOR  
-01, -021 & -081 ASSY

(A) 4 PAIR CYLD HLES .0259  $\pm .0005$  DIA

(B) 4 PAIRS FUEL HLES .0243  $\pm .0005$



DETAIL SHOWING ORIFICE  
GEOMETRY 4-TIME SIZE

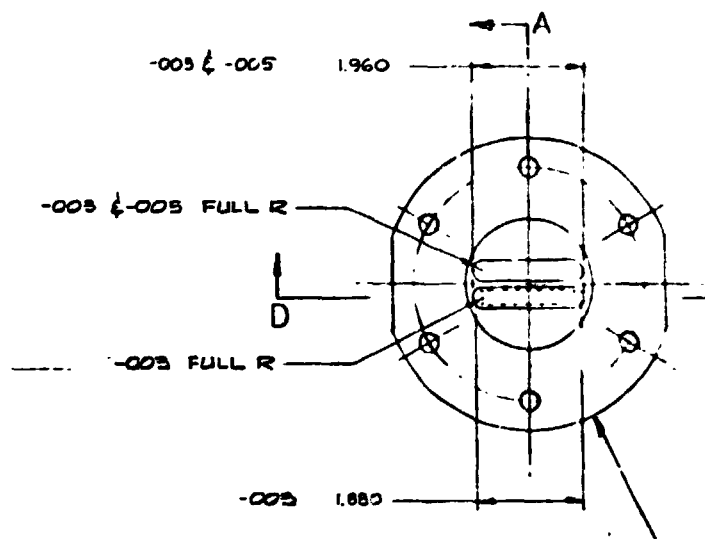
ASSY NO.	A $\pm 0^{\circ} 30'$	B BASIC	C BASIC
-011	45°	.100	.417
-021	54°	.104	.457
-031	22° 30'	.107	.488
-041	45°	.100	.265
-051	54°	.104	.285
-081	22° 30'	.107	.306

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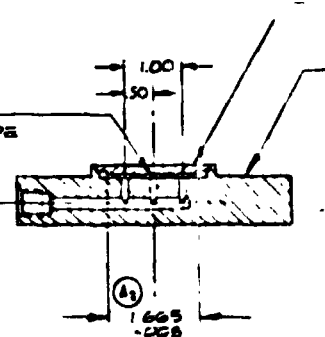
The diagram illustrates the geometry of a projectile impact on a target. A projectile, shown as a hatched oval, is moving towards a target, also shown as a hatched rectangle. The impact is characterized by three key parameters:

- B IMPINGEMENT HEIGHT:** The vertical distance from the base of the target to the point of impact.
- A INCLINATION ANGLE:** The angle between the vertical axis and the line of sight from the base of the target to the point of impact.
- 60° IMPINGEMENT ANGLE:** The angle between the projectile's path and the normal to the target's surface at the point of impact.

LOC 3 & LOC 5  
SHAFF T. GOLD SEAL

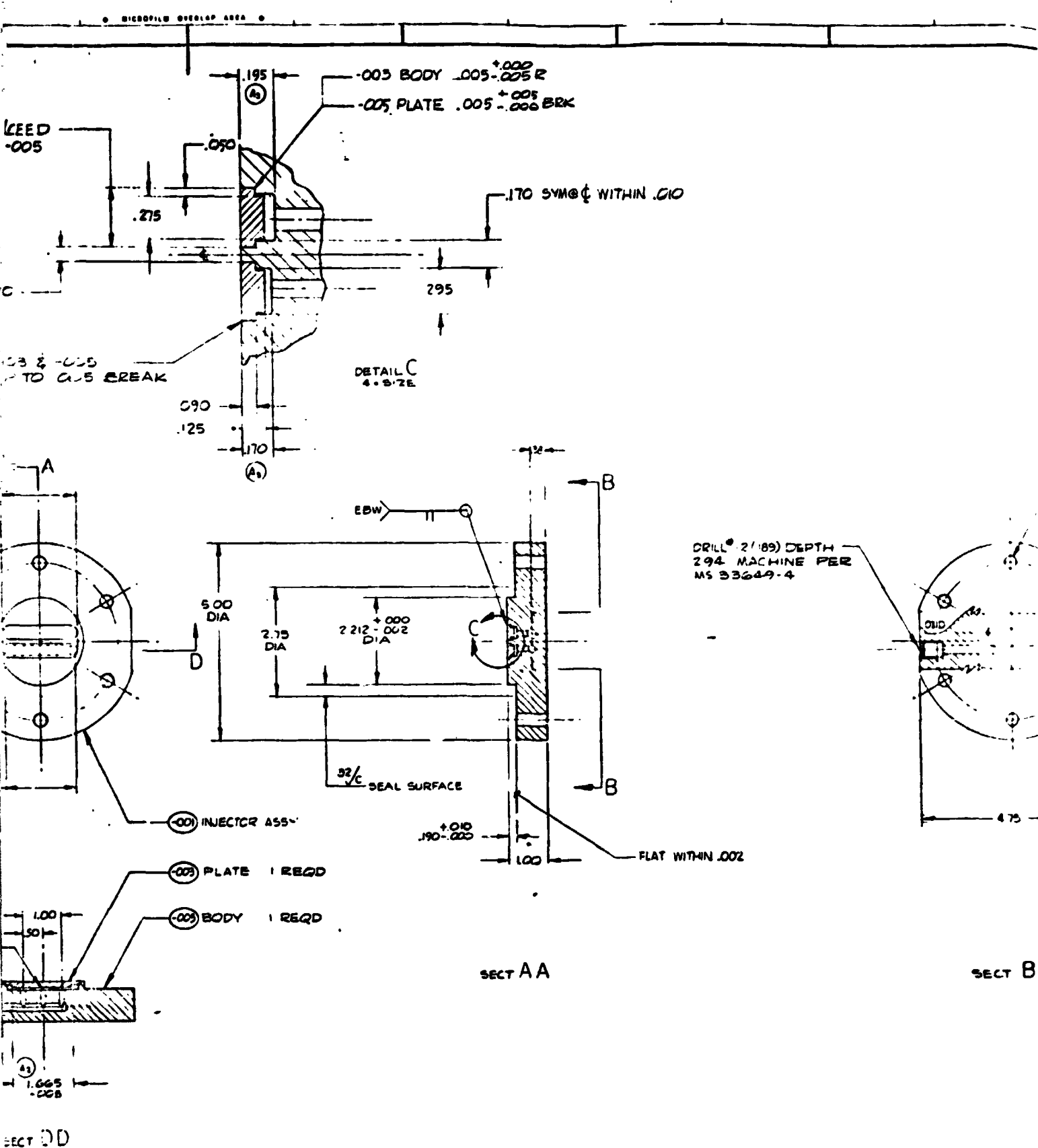


DRILL 2 (1094) 3 HOLES —  
AS SHOWN ON OXID SIDE  
DRILL 28 (1405) 3 HOLES  
AS SHOWN, FUEL SIDE



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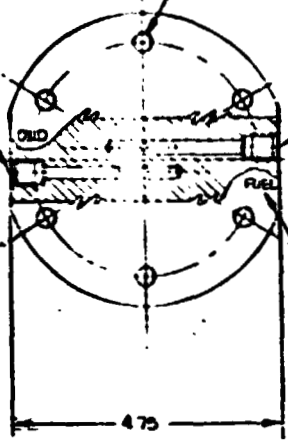
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DRILL # (244) THRU  
6 HOLES EC SP N.T.H. 5 DIA  
ON A 1.000 RSC DA

DRILL "D" (238) DEPTH 2.94  
MACHINE PER MS 53649-4

IMPRESSION STAMP  
1/8 HIGH LETTERS  
2 PLS AS SHOWN



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- 261
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- C11
- C01

- 5) ROTARY HEAD ECM ONLY. EACH PAIR OF HOLES MUST IMPINGE WITHIN .005 OF BASIC DIMS B & C
- 4) HYDROSTATIC PROOF TEST @ 170 PSIG FOR 2
- 3) CLEAN PER RAC110-015
- 2) IDENTIFY PER RAC110-005
- 1) MACHINE PER RAC110-002

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FIGURE 2

INJECTOR ASSY OF ONE SUB-SCALE

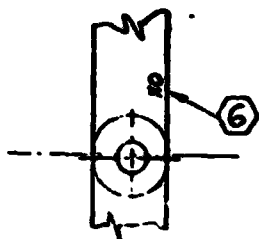
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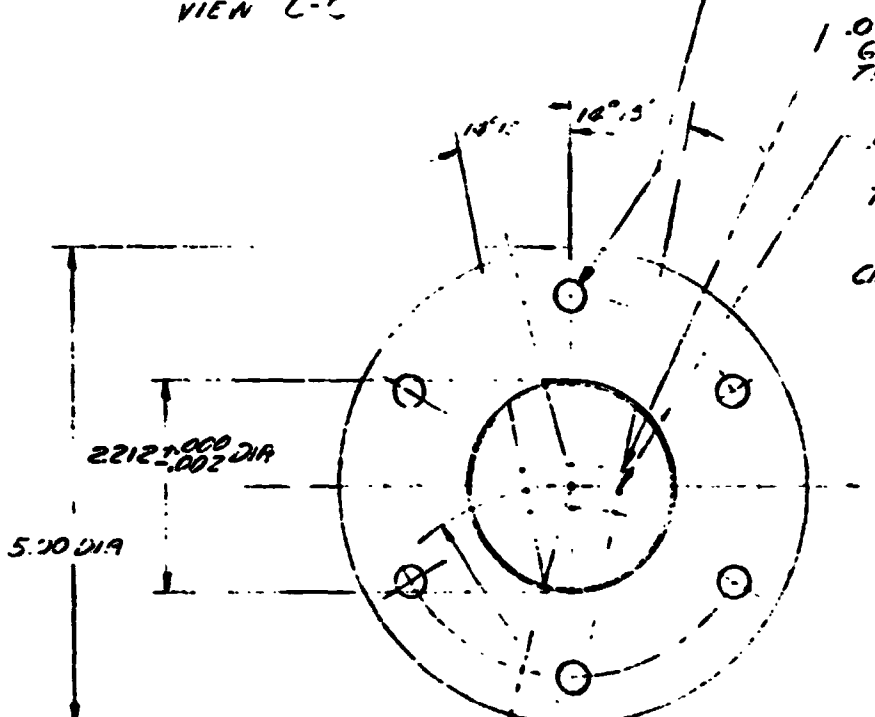
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DRILL  $\frac{1}{32}$  (3433) 6 HOLES  
EQUALLY SPACED WITHIN .010  
ON A 6.000 R.C. DIA



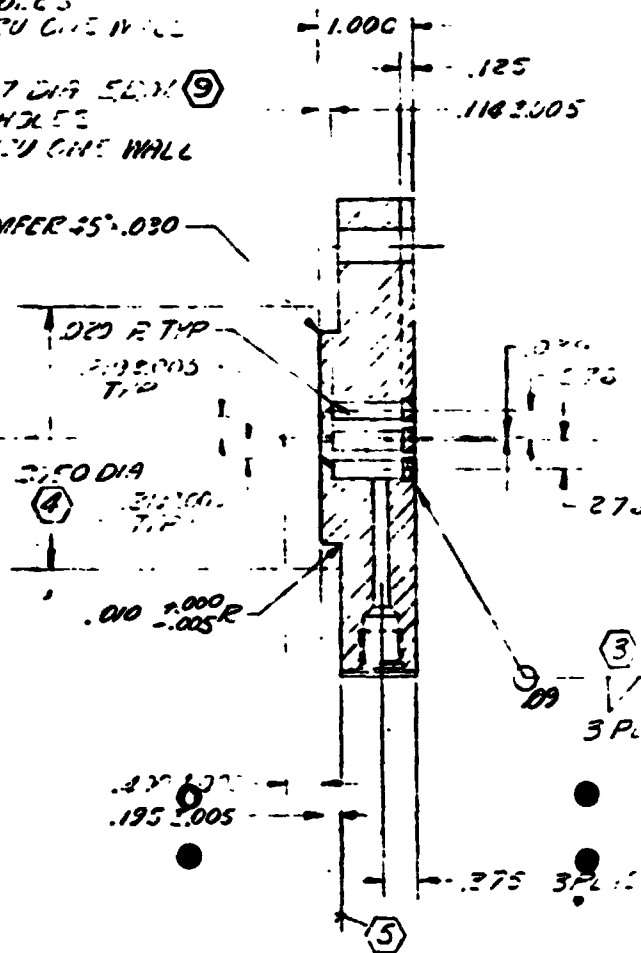
VIEW C-C



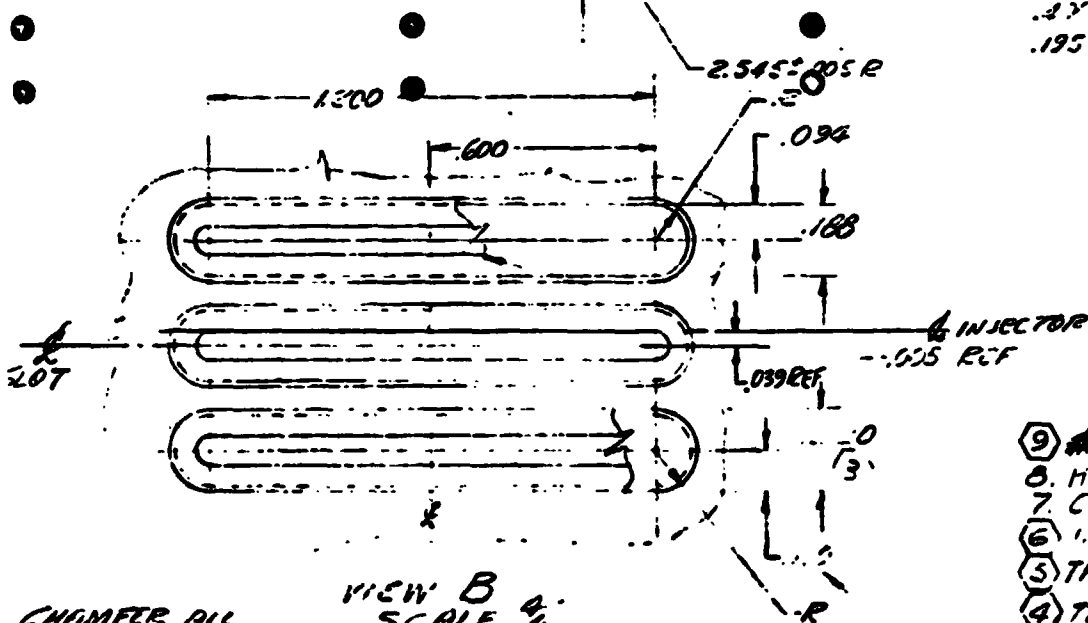
.032 DIA EDM (9)  
6 HOLES  
THRU ONE WALL

.057 DIA EDM (9)  
3 HOLES  
THRU ONE WALL

CHAMFER 25° .030

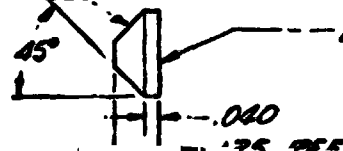


SECTION A-A



VIEW B  
SCALE  $\frac{4}{1}$

CHAMFER ALL  
ROUND AS SHOWN



DETAIL - .005  
SCALE  $\frac{4}{1}$

- (9) EDMA HEAD EDM ORIFICE
- (8) HYDROSTATIC PROOF CHECK AT
- (7) CLEAN PER RA 0110-015
- (6) IMPRESSION STAMP 12 154 LET
- (5) THIS SURFACE TO BE FLAT WITHIN
- (4) THIS SURFACE SHALL BE FREE OF  
SCRATCHES, AND OTHER IMPERFECT  
WOULD IMPAIR THE SEALING FUN
- (3) FUSION WELD PER  
RA 0107-027 GAP .010 MAX  
2 IDENTIFY PER RA 0104-008  
1 MACHINE PER RA 0103-002

NOTE: UNLESS OTHERWISE SPECIFIED





## TEST FACILITIES

### TEST STAND

The engine firings were performed on Lima Stand in the Propulsion Research Area (PRA) at the Rocketdyne Santa Susana Field Laboratory. A simplified schematic diagram of this facility is shown in Fig. 4. Details of the propellant tanks and pressurization systems are shown in Fig. 5.

### Fuel Heating System

The MMH is batch heated to the desired temperatures ( $100^{\circ}$ - $250^{\circ}$ F) in only the limited quantities required for several engine firings. This is accomplished through use of a 4.5 gallon heat exchanger located immediately upstream of the fuel main valve. In this heat exchanger, hot water flows inside four concentric coils of  $\frac{1}{4}$ -inch O.D. stainless steel tube and provides a temperature limited heat source for the somewhat thermally sensitive fuel. As shown in Fig. 4, the heating water is circulated in a closed system from a steel reservoir tank, through a 2.5 gpm Burke pump and an 18-kilowatt Chromalox electrical heater, and then through either the heat exchanger or a bypass loop back to the reservoir. An alternate supply of cold water can be introduced into the system to quickly cool the heat exchanger between tests and, thus, permit test personnel to work in the immediate vicinity of the heater and test stand. Heat-up and cool-down times for the system are both less than 10 minutes.



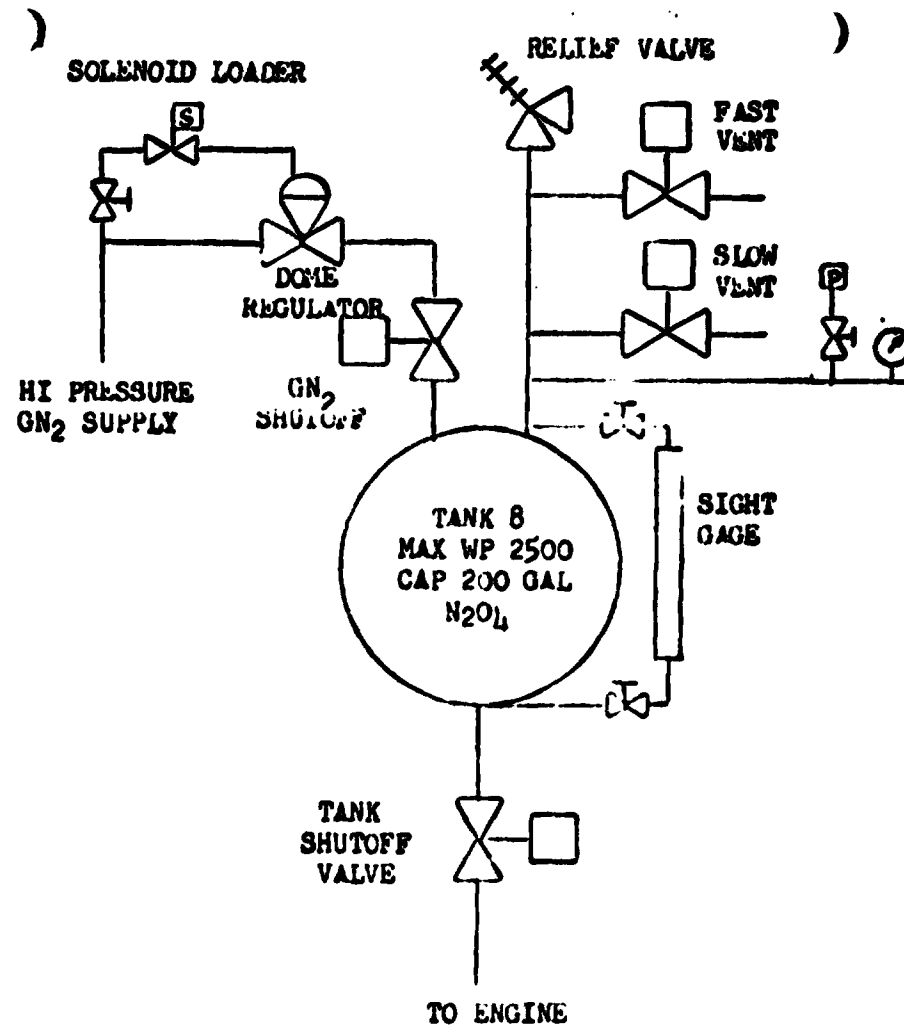
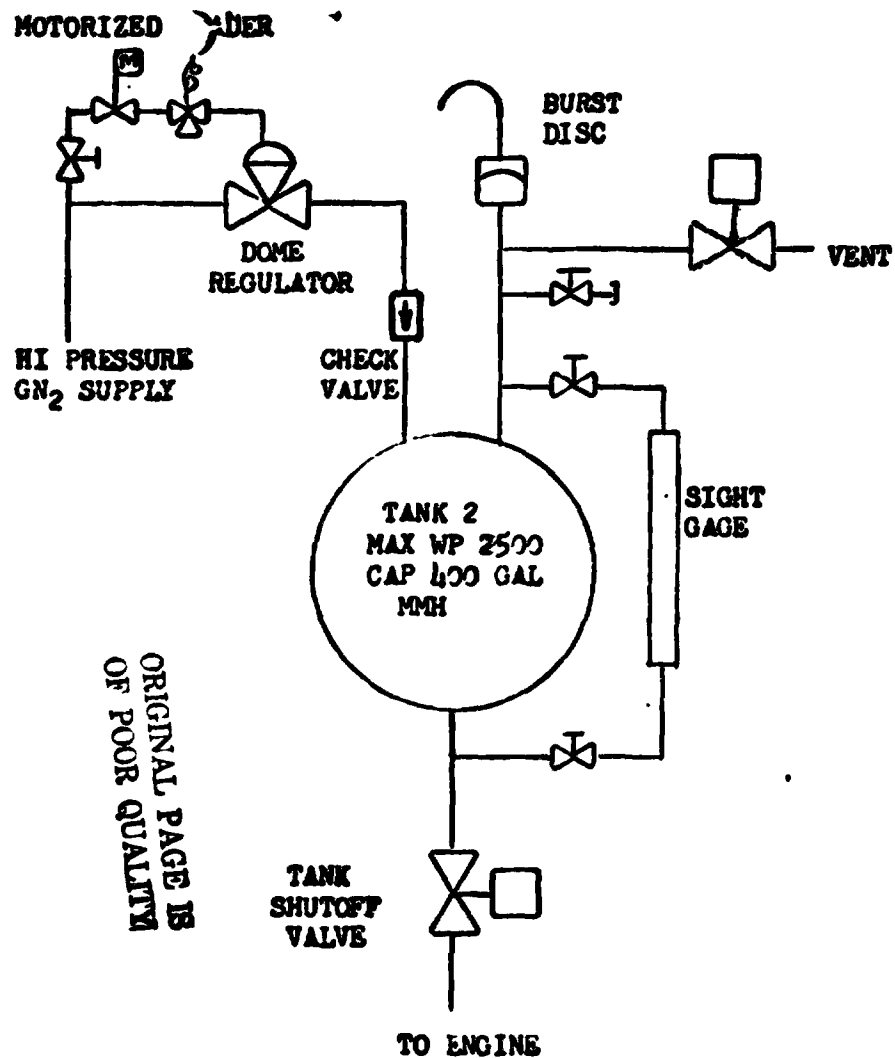


Figure 5. Fuel and Oxidizer Tank Pressurant Systems

### Oxidizer Heater System

Boiling fresh water (100°F) is employed to heat the oxidizer. The oxidizer heater consists of a barrel of hot water with 3 coils through which the  $N_2O_4$  flows.

### INSTRUMENTATION

Table 2 summarizes the parameters measured during the engine firings, the instrumentation (transducers) utilized for these measurements, and the method of recording the data.

The pressures, temperatures, and volumetric propellant flowrates required to calculate characteristic exhaust velocity efficiency,  $\eta_{c*}$ , are recorded on direct reading Dynalog or strip chart recorders or on a low speed oscillograph for immediate analysis and test control. Precision recording for computerized analysis is made with the multi-channel Beckman Digital Data system for the low frequency measurements. The high-frequency pressure oscillations which may be detected by a model 317 Photocdn transducer are recorded on a high speed oscillograph and an FM tape recorder.

TABLE 2 INSTRUMENTATION LIST FOR SUBSCALE MOTOR FIRINGS

	PARAMETER/MEASUREMENT	SYMBOL	TRANSDUCER EMPLOYED	RECORDING SYSTEM		
				BKM	DIGR	OSC.
1	Fuel Tank Pressure	PTF	Taber*		X	
2	Fuel Line Pressure #1	TLF-1	I/C TC**	X	X	
3	Fuel Heater Temperature #1	TMH-1	I/C TC**		X	
4	Fuel Heater Temperature #2	TMH-2	I/C TC**		X	
5	Fuel Heater Temperature #3	TMH-3	I/C TC**		X	
6	Fuel Flowrate #1	WF-1	Turbine Flowmeter	X	X	X
7	Fuel Flowrate #2	WF-2	Turbine Flowmeter	X	X	X
8	Fuel Flowmeter Temperature	TLF-2	I/C TC	X	X	
9	Fuel Injection Temperature	TIF	I/C TC			
10	Fuel Injection Pressure	PIF	Taber	X	X	X
11	Oxidizer Tank Pressure	PTU	Taber		X	
12	Oxidizer Line Temperature	TLO-1	I/C TC	X	X	
13	Oxidizer Flowrate #1	WOX-1	Turbine Flowmeter	X	X	X
14	Oxidizer Flowrate #2	WOX-2	Turbine Flowmeter	X	X	X
15	Oxidizer Flowmeter Temp.	TLO-2	I/C TC	X	X	
16	Oxidizer Injection Temp.	TIO	I/C TC	X	X	
17	Oxidizer Injection Pressure	P10	Taber	X	X	X
18	Chamber Pressure #1	PC-1	Taber	X	X	X
19	Chamber Pressure #2	PC-2	Taber	X	X	
20	Chamber Photocon	PCPH	Photocon			X***
21	Water Tank Temp	TWT	I/C TC		X	
22	Water Heater Temp	TWHO	I/C TC		X	
23	Inlet Water Temp****	TWFI	I/C TC		X	
24	Outlet Water Temp****	TWFO	I/C TC		X	

- \* Taber Strain Gage Pickup
- \*\* Iron Constantan Thermocouple
- \*\*\* Photocon on tape also
- \*\*\*\* At MMH Batch Heater

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## RESULTS AND DISCUSSION

A total of 81 tests were conducted to define the effect of element geometry and operating conditions on  $c^*$  performance. For each element type the following variables were investigated.

Like-doublet - (1) cant angle  
(2) spacing  
(3) fuel temperature  
(4) oxidizer temperature  
(5) mixture ratio  
(6) chamber pressure  
(7) chamber length

Unlike-Triplet - (1) fuel temperature  
(2) oxidizer temperature  
(3) mixture ratio  
(4) chamber pressure  
(5) chamber length

The test program was constructed to define the performance characteristics over a wide range in operating characteristics; however, the bulk of the data were obtained at typical OME regeneratively-cooled thrust chamber operating conditions. A complete summary of the tests are given in Table 3. In this Table the pertinent operating parameters are presented along with pertinent remarks. The  $c^*$  efficiency values presented are based on the pressure measured at the beginning of the nozzle contraction (corrected for the

TABLE 3. SUMMARY OF OME SUBSCALE TEST DATA

Page 1 of 9

Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c^*}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
90	225	34	0.146	0.150	4	137.6	1.76	80	84	91.2	
91						132.6	1.75	81	84	91.7	
92						126.7	1.68	82	82	92.3	
93						127.7	1.62	79	82	91.9	
94						124.4	1.41	79	83	91.9	Fuel Orifice Plugged
97						129.4	1.61	93	93	91.5	Fuel Orifice Plugged
98						124.3	1.54	92	212	86.7	
99						122.2	1.42	90	231	84.5	
100						121.3	1.83	89	235	83.7	
101						128.2	1.62	91	105	90.9	
102						127.7	1.47	89	98	90.9	
129						127.4	1.65	74	83	95.9	
130						127.9	1.93	73	84	92.0	
131						114.4	1.76	72	83	93.8	
132						120.9	1.73	76	194	88.7	
133						120.4	1.59	78	232	89.7	

## SUMMARY OF ONE SUBSCALE TEST DATA (Cont.)

Page 2 of 9

Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c*}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
134	225	34	0.146	0.150	4	118.2	1.57	75	247	86.7	
135						104.1	1.81	75	245	87.4	
136						107.8	1.49	75	207	89.5	
137						134.5	1.62	75	206	88.2	
103	226	45	0.114	0.150	4	124.5	1.73	86	84	90.2	
104						127.8	1.50	85	85	91.4	
105						123.2	1.98	84	86	87.8	
106						141.4	1.70	85	86	89.6	
107						109.3	1.72	86	85	89.5	
108						124.4	1.56	88	174	89.0	
109						122.5	1.62	88	189	88.1	
110						119.4	1.86	86	197	85.1	
111						119.1	1.74	88	222	87.3	
112						133.4	1.71	87	215	86.0	
113						105.8	1.67	88	194	87.8	
114						118.9	1.73	86	104	88.7	



## SUMMARY OF ONE SUBSCALE TEST DATA (Cont.)

Page 3 of 9

Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c+}$ , %	Remarks .
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
115	224	22½	0.178	0.150	4	119.8	1.64	91	88	26.6	
116						120.0	1.48	87	87	85.3	
117						119.6	1.92	86	87	86.1	
118						131.4	1.69	85	86	83.6	
119						108.3	1.68	83	86	88.3	
120						121.2	1.62	66	65	87.5	
121						116.2	1.63	65	173	83.0	
122						116.6	1.44	67	203	82.0	
123						115.8	1.78	65	207	83.4	
124						125.9	1.57	65	216	81.0	
125						104.7	1.62	63	200	84.4	
126						112.8	1.58	68	248	79.9	
127						119.2	1.75	66	253	78.5	
128						101.3	1.60	66	256	80.8	

## SUMMARY OF OME SUBSCALE TEST DATA (Cont.)

Page 4 of 9

Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c+}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
192	225	34	0.146	0.150	10	146.4	1.92	70	72	92.3	
193						130.2	1.66	71	72	92.1	
194						127.7	1.57	71	171	90.3	
195						126.0	1.55	70	210	89.8	
196					7	126.6	1.66	67	202	88.9	
197					4	131.3	1.78	59	200	87.1	
198					.	128.7	1.77	61	221	86.8	
199	43	NA	NA	NA	10	125.5	1.64	62	185	87.6	
200						122.8	1.56	62	208	88.5	
201					7	124.0	1.65	59	208	86.3	
202					4	126.1	1.57	60	211	86.0	Osc. Malfunction
203						123.2	1.55	81	168	87.7	Mild Instability
204						118.8	1.57	85	181	84.2	Unstable
205						120.7	1.49	74	210	83.7	Unstable
206						120.3	1.47	91		85.6	Mild Instability
207						121.5	1.48	102	228	85.5	Mild Instability

## SUMMARY OF ONE SUBSCALE TEST DATA (Cont.)

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Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c*}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
208	225	34	0.146	0.150	4	122.2	1.63	111	219	83.6	
209						116.8	1.41	125	214	85.7	
210						116.2	1.46	123	228	83.8	
211	224	22½	0.178	0.150	4	117.2	1.72	50	190	78.6	
212						114.4	1.78	50	209	78.1	
213						112.1	1.64	52	204	79.1	
214	11	45	0.417	0.100	4	125.9	1.67	49	190	88.7	
215						124.5	1.58	49	196	88.3	
216	41	45	0.265	0.100	4	120.7	1.56	51	189	86.7	
217						121.9	1.70	51	204	87.4	
218	11	45	0.417	0.100	4	126.3	1.64	60	60	92.9	
219						126.5	1.53	59	60	91.3	
220						-	-	-	-	-	Flowmeter Malfunction
221						-	-	-	-	-	Flowmeter Malfunction

## SUMMARY OF ONE SUBSCALE TEST DATA (Cont.)

Page 6 of 9

Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c+}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
222	11	45	0.417	0.100	4	124.2	1.34	65	69	87.7	
223						121.5	1.44	64	215	85.5	
224	51	34	0.285	0.104	4	123.6	1.43	68	72	85.1	
225						125.1	1.60	64	72	86.6	
226						118.6	1.57	66	222	81.4	
227						125.6	1.52	66	77	87.3	
228	?	34	0.437	0.104	4	122.8	1.52	64	222	84.9	
229						123.2	1.60	53	53	84.1	
230						120.6	1.63	53	202	80.6	
231						120.2	1.56	53	230	79.1	
232	11	45	0.417	0.100	4	128.0	1.53	55	76	88.8	
233						125.0	1.54	55	220	87.6	
234						121.3	1.40	54	232	87.3	

## SUMMARY OF OME SUBSCALE TEST DATA (Cont.)

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Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c*}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
235	41	45	0.265	0.100	4	125.0	1.44	58	64	89.5	
236						121.4	1.61	57	201	86.0	
237						121.6	1.55	56	225	86.1	
238	224	22½	0.178	0.150	4	121.4	1.40	59	67	83.1	
239						120.9	1.48	58	68	83.5	
240						113.5	1.57	58	215	78.6	
241						113.7	1.60	56	221	79.0	
242	11	45	0.417	0.100	4	126.8	1.45	67	68	89.8	
243						128.1	1.59	66	69	90.8	
244						130.2	1.57	65	69	89.6	
245						129.6	1.57	71	124	88.9	
246						130.5	1.68	70	125	89.1	
247						129.8	1.64	70	181	88.9	
248						128.6	1.44	68	172	91.7	
249						126.7	1.50	70	247	90.7	
250						127.2	1.70	71	256	90.2	

## SUMMARY OF ONE SUBSCALE TEST DATA (Cont.)

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Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c+}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
251	43	NA	NA	NA	7	124.2	1.35	51	186	92.4	Flowmeters Inconsistent
252						122.8	1.43	50	221	92.3	
253						123.2	1.48	50	239	90.2	
254	225	34	0.146	0.150	4	127.0	1.46	54	65	95.3	
255						123.5	1.47	55	213	89.2	
256						121.8	1.53	58	237	88.6	
257						125.4	1.56	80	193	89.4	
258						124.7	1.46	83	218	89.3	
259						125.2	1.44	92	213	91.0	
260						123.9	1.44	104	230	91.7	
261	223	22½	0.188	0.188	4	121.4	1.37	61	52	88.5	
262						119.4	1.31	63	53	88.5	
263						110.2	1.36	62	212	80.3	
264						107.3	1.30	69	233	78.2	

## SUMMARY OF ONE SUBSCALE TEST DATA (Concluded)

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Test No.	Injector				Chamber Length, Inches	P <sub>c</sub> , Psia Nozzle Stagnation	Mixture* Ratio	T <sub>OX</sub> , °F	T <sub>f</sub> , °F	$\eta_{c+}$ , %	Remarks
	I.D. No.	Cant Angle	Spacing, Inches	Impingement Height, In.							
265	11	45	0.417	0.100	4	120.8	1.51	102	215	86.6	
266						118.6	1.48	112	235	86.9	
267						117.6	1.45	112	214	86.9	
268						116.1	1.45	124	220	85.1	
269	11**	45	0.417	0.100	4	121.7		70	211	93.6	Flowmeter Malfunction
270						121.2		70	233	93.8	Flowmeter Malfunction
271						120.3		56	238	104	Flowmeter Malfunction

\*Oxidizer flowrate based on #1 flowmeter

\*\*Oxidizer orifices enlarged to 0.0289" diameter.

dynamic head). No friction, heat loss or other correction was applied to these basic calculations. During the testing of the 224 through 226 injectors (tests 90 through 128) some problems were encountered with plugging of the orifices. Besides using the measured  $c^*$  values as an indicator of plugging, the injectors were water flowed pre- and post-test and visual observations of the flow characteristics made. When plugging was observed repeat tests were made. In addition, to insure the most accurate determination of flowrate dual flowmeters were employed in the oxidizer system. Near the end of the test series the flowmeters began to drift. It was noted that as much as a 5 or 7% difference in  $c^*$  efficiency could be calculated depending on the flowmeter used. Based on the checkout tests (i.e., repeat ambient tests between the initial series of experiments and the final test series) the No. 1 flowmeter gave the same results and was therefore used in all calculations of the experimental data. Lastly, during the last series of tests with the enlarged oxidizer orifices on injector 011 the No. 1 flowmeter behaved erratically and gave  $c^*$  efficiencies as high as 104 percent. The flowmeter was removed and Teflon tape found on the rotor. As a consequence these data are invalid. Due to funding limitations repeat tests were not accomplished.

## PERFORMANCE

### Like-Doublet Injectors

Summary plots of the data as functions of the variables investigated are presented in Figures 6 through 8. Since a large number of variables were studied it is difficult to construct data plots where only one variable was investigated. Because of this it was impossible to show plots for all



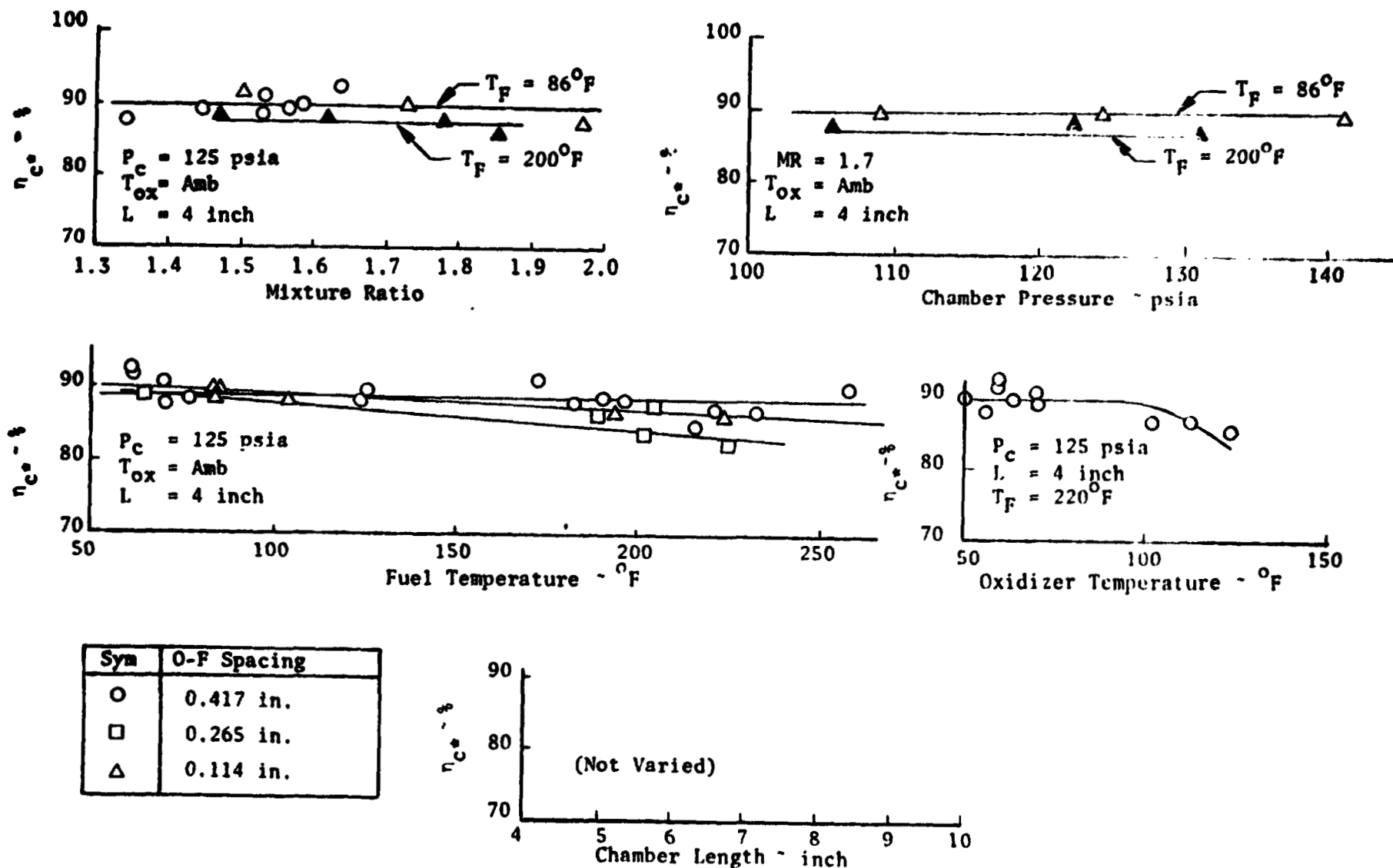


Figure 6. Summary of Experimental Results for 45° Cant Angle Like-Impinging Doublet Injectors

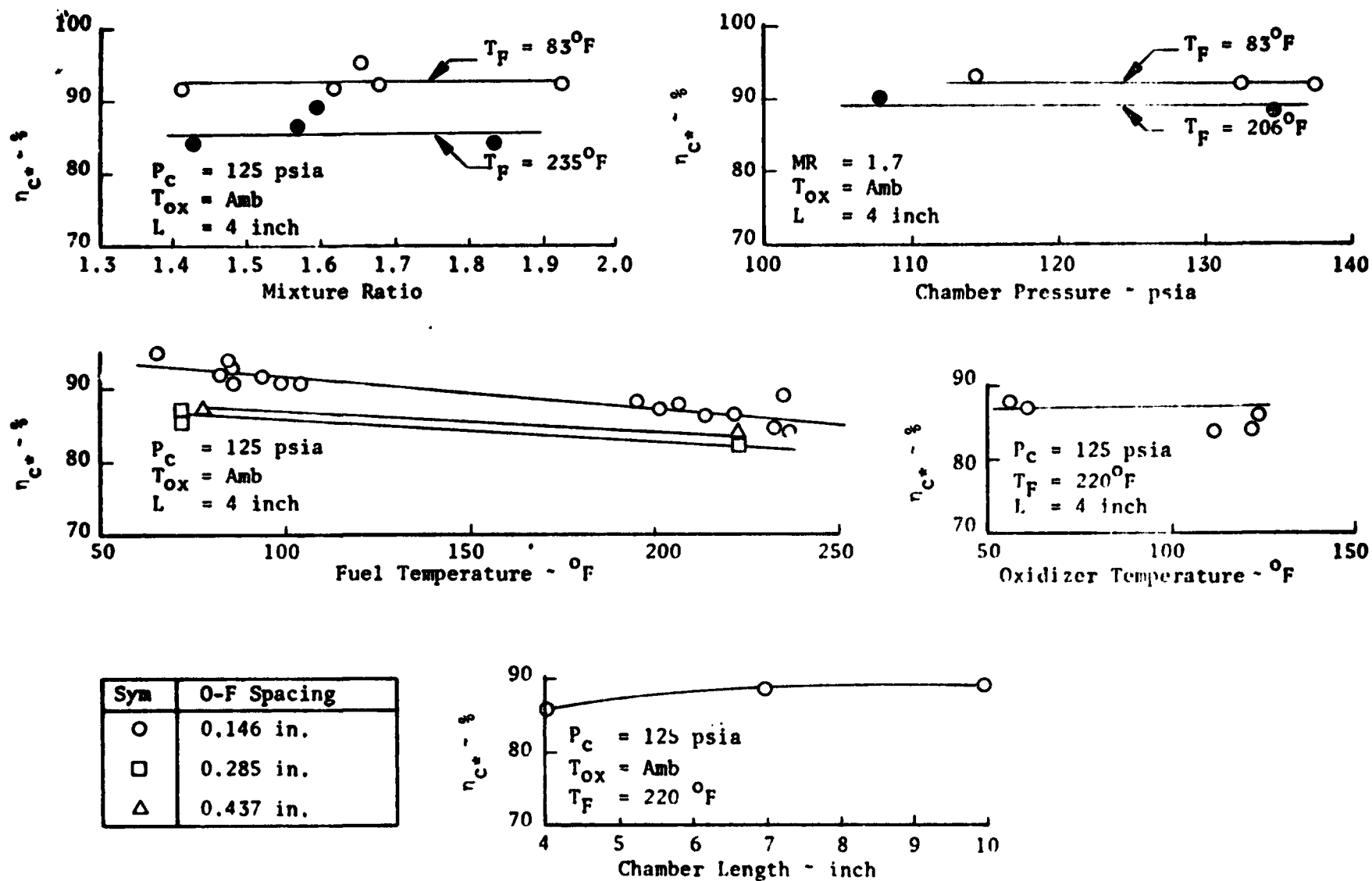
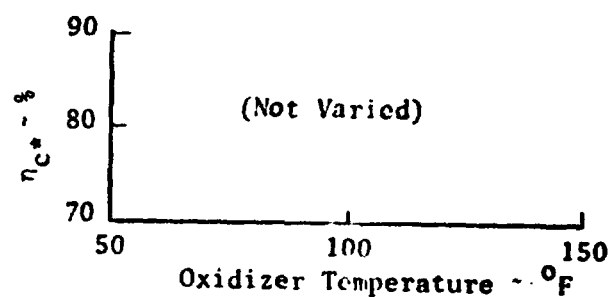
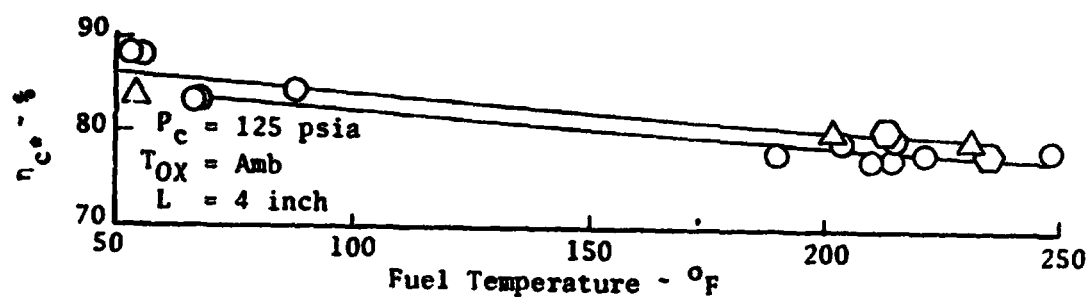
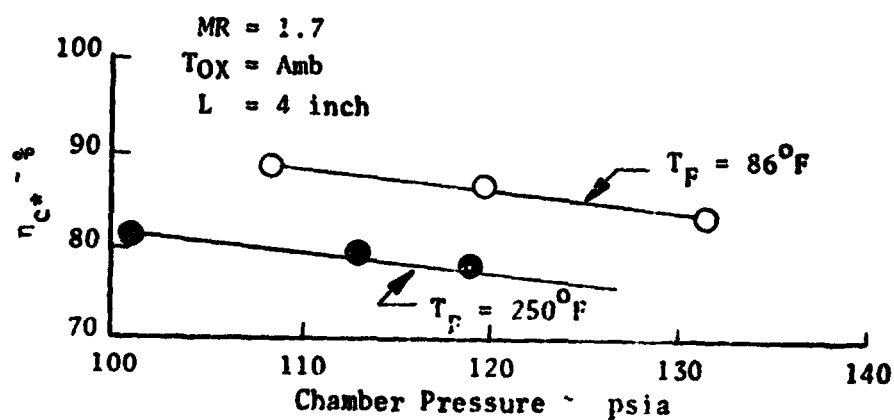
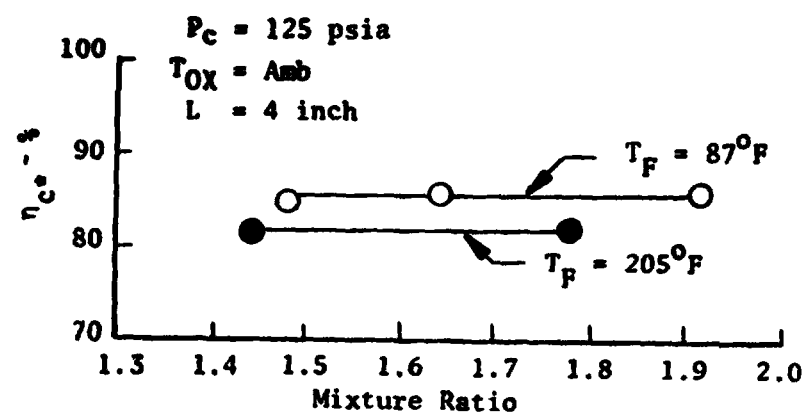


Figure 7. Summary of Experimental Results for 34° Cant Angle Like-Impinging Doublet Injectors



Sym	O-F Spacing
○	0.178 in.
⬡	0.178 in.
△	0.306 in.

\*3 Element Injector

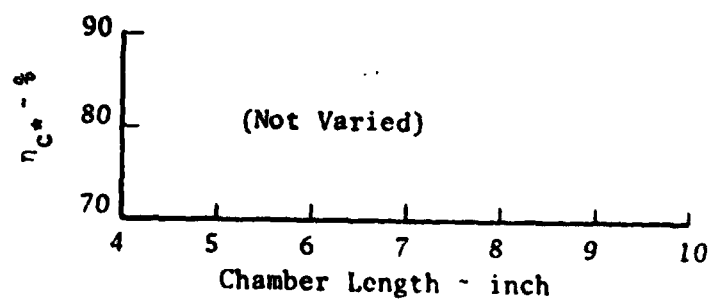


Figure 8 . Summary of Experimental Results for  $22\frac{1}{2}^\circ$  Cant Angle Like-Impinging Doublet Injectors

variables for every configuration studied. As can be noted from the figures, for the 45 degree cant angle injectors, only the chamber length was not measured. For the 34-degree cant angle injectors all variables were studied for one configuration. The least investigated was the 22½ degree configuration. Oxidizer temperature and chamber length were not varied since this configuration had the least potential for achieving maximum c\* efficiency.

Mixture Ratio. Data are presented for both ambient and heated fuel in Figures 6 through 8. Regardless of fuel temperature, mixture ratio, over the range from 1.3 to 2.0 had no appreciable effect on the c\* efficiency. This result suggests that, for these design conditions, mixing is not influenced by the relative momenta of the sprays.

Chamber Pressure. For one configuration of each of the cant angle injectors chamber pressure was varied from about 105 to 140 psia with both heated and ambient fuel. Identical results were obtained with ambient and heated fuel. The results show that for the 45 and 34 degree cant angles, increasing the chamber pressure did not affect c\* performance. However, at 22½ cant degree angle, chamber pressure had a strong influence on the resultant c\* efficiency. The physical reason for this type of characteristic is not obvious. It is unlikely that this element experiences popping and if reactive stream separation occurred then it would be expected that performance would increase with increasing chamber pressure since the momentum for mixing would be increasing. In addition, increased fuel temperature should result in increased dependency of chamber pressure on c\* efficiency. It is certainly possible that some

degree of reactive stream separation is occurring; however, it is unlikely that this is causing the reduction in  $c^*$  efficiency at fixed fuel temperature.

The performance decrease with increased chamber pressure with the 22½ degree design is probably the result of the sprays penetrating through each other, since this cant angle results in (1) the largest distance between the contact of the sprays, (2) increased injection velocity results in shorter breakup distance of the sheets, and (3) increased chamber pressure results in increasing the spray momentum. This hypothesis could be verified by cold flow of the elements.

Fuel Temperature. One of the more startling results was the effect that fuel temperature had on  $c^*$  efficiency. For all but one configuration, increasing the fuel temperature resulted in decreasing the  $c^*$  efficiency. This characteristic suggests that reactive stream separation is occurring. This result was surprising in that the advantage of a like-impinging doublet injector is that it should be (1) insensitive to popping, and (2) since mixing occurs in the droplet phase of mixing (i.e., rather than by impingement of jets or sheets), reactive stream separation should not occur. The 45 degree cant angle and 0.417-inch spacing resulted in constant  $c^*$  performance with increased fuel temperature. This is discussed in more detail in a subsequent section.

Oxidizer Temperature. The oxidizer temperature was varied from about 50 to 125 degrees Fahrenheit using 45 and 34 degree cant angle injectors. The data

show that  $c^*$  efficiency was not affected by the oxidizer temperature until it increased above about 100 to 110°F. Here again, once the oxidizer temperature is sufficiently high that substantial gas generation will occur before mixing then regardless of the configuration reactive stream separation will occur. Taking high speed movies of a single-element injector under typical hot fire conditions would reveal the onset of reactive stream separation.

Chamber Length. Chamber length was varied from 4 to 10 inches to determine the performance characteristics. Two results can be determined from these measurements, (1) whether substantial secondary mixing occurs, and/or (2) whether the performance is mixing limited. Based on the results shown on Fig. 7,  $c^*$  performance tends to level off at about 89 percent suggesting that this represents a mixing limited value. This level is not surprising since the elements are arranged in a single row and inter-element mixing cannot occur. It does not appear that substantial secondary mixing occurs with the configuration evaluated.

Element Size. The data obtained using a three-element like-doublet injector designed with the same cant angle and spacing as the 4-element design (22½ degree cant angle and 0.178 spacing) are presented in Fig. 8. Comparison of the data reveals that for this configuration no reductions in  $c^*$  efficiency occurred suggesting that the thrust chamber/injector configuration is mixing limited rather than vaporization rate limited (unless the secondary droplet sizes are identical).

Equal Oxidizer and Fuel Momentum. Due to flowmeter malfunction the experimental results for this portion of the study are invalid. The injector is available for evaluation at a later date.

Cant Angle/Element Spacing. Optimization of the mixing between a fuel and oxidizer like-doublet element is achieved by two major geometric variables, (1) cant angle, and (2) spacing between the oxidizer and fuel element. In order to avoid popping or reactive stream separation the element must be designed such that inter-propellant mixing does not occur until the individual sheets experience breakup into droplets. To determine the optimum configuration, elements were designed over a wide range in cant angle (45 to 22½ degrees) and spacing (~ 0.11 to 0.42 inch) and experiments conducted at both ambient and heated fuel conditions. The results presented in the previous figures have been cross plotted at constant temperature in Fig. 9. Note that both ambient and heated fuel (220°F) conditions are presented. For the L/D #2 full-scale OME injector, the spacing is 0.1 inch with a 34° cant angle. For this case whether the fuel is ambient or heated the 34° cant angle provides optimum c\* efficiency. However, increased performance can be realized if the spacing is increased to 0.45 inch with a 45° cant angle. The improved performance is a direct result of the insensitivity of performance to fuel temperature at these conditions as illustrated previously, Fig. 6.

#### Unlike-Triplet Injectors

This injector was studied previously during a Company IR&D program and for completeness the data are included in the summary plot of Fig. 10. Since

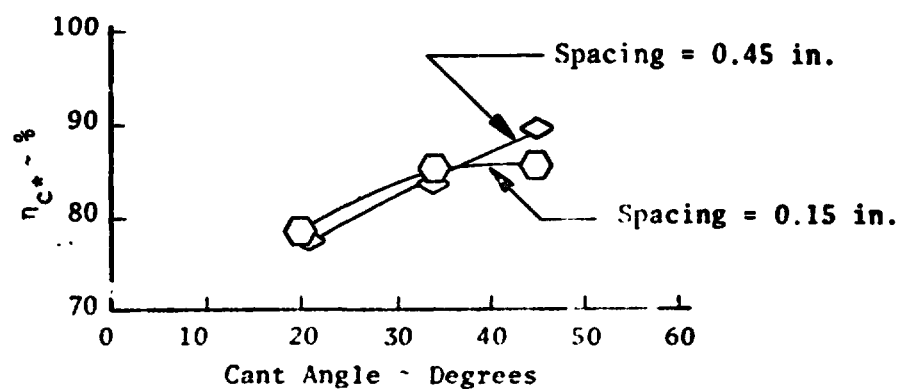
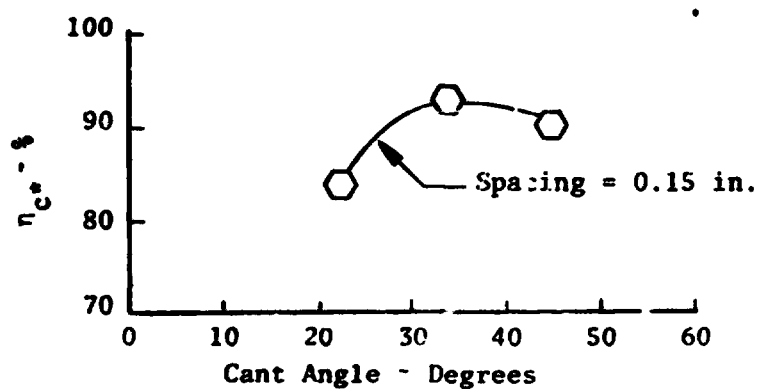
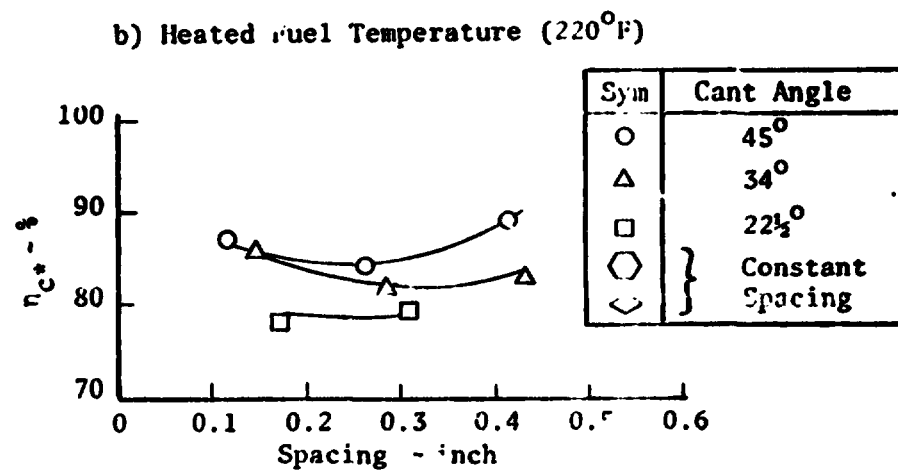
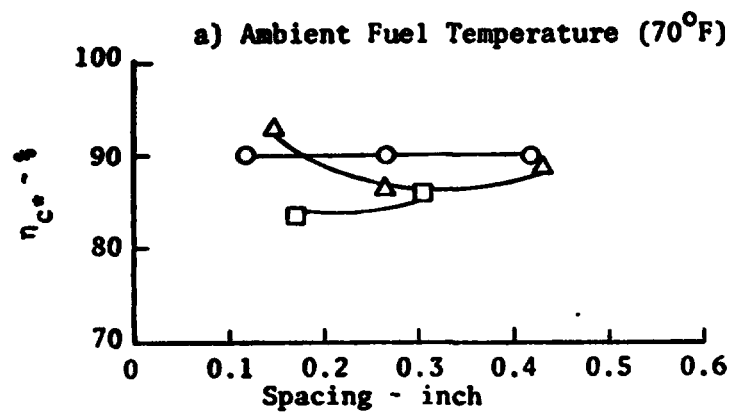


Figure 9 . Effect of Cant Angle and Spacing on C\* Efficiency for Like-Doulet Injector with Ambient and Heated Fuel



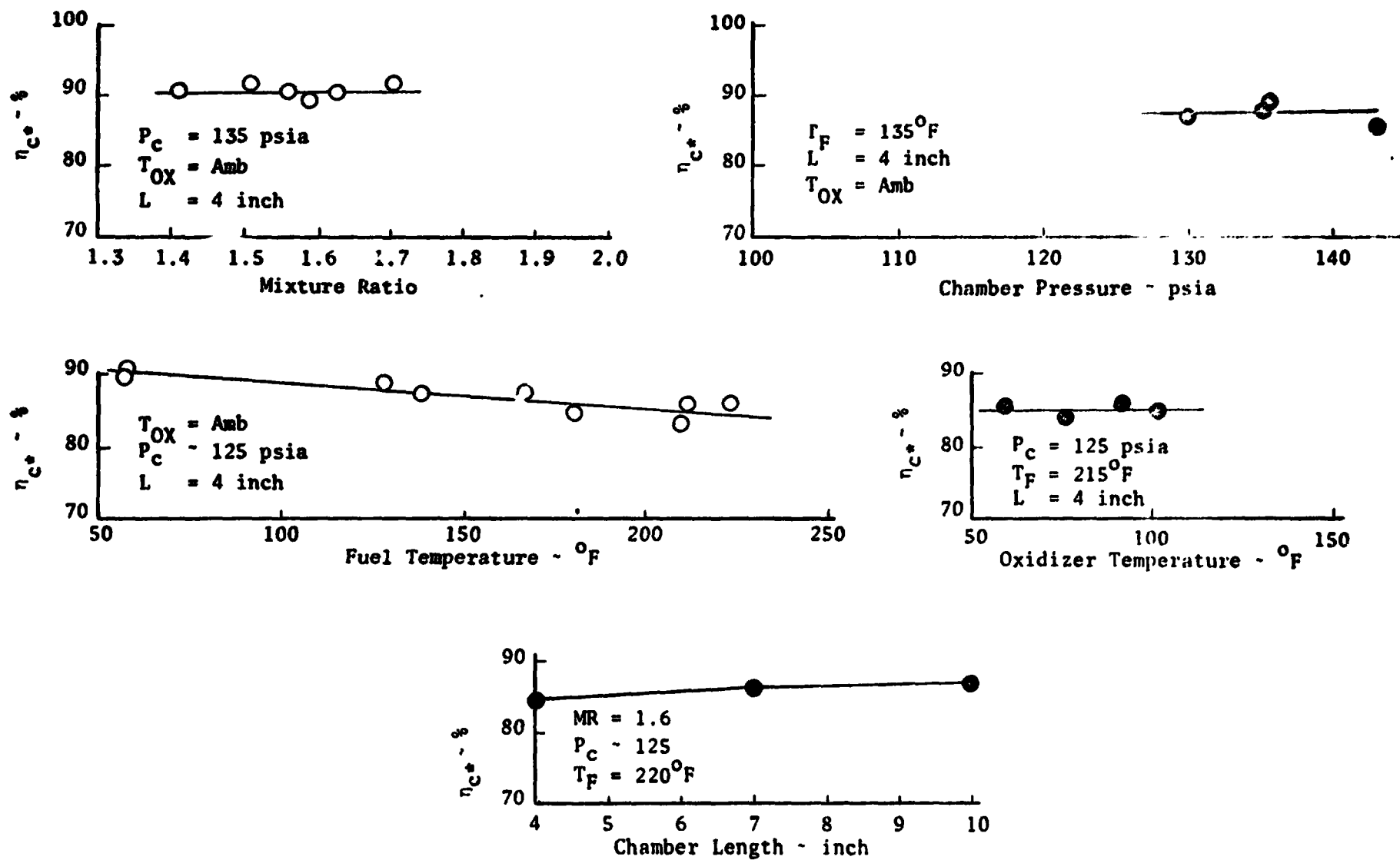


Figure 10. Summary of Experimental Results for an Unlike-Impinging Triplet Injector

some instabilities were encountered with this element, only the data where steady-state operation occurred is shown. Stability is discussed in a separate section of this report.

Mixture Ratio. For this element, at ambient propellant temperature conditions, mixture ratio was varied holding other variables constant. The  $c^*$  efficiency was not affected by mixture ratio. These results are identical to that found for the like-impinging doublet injector.

Chamber Pressure. Chamber pressure effects on  $c^*$  efficiency at heated fuel conditions are shown on Fig. 10 . At these conditions  $c^*$  efficiency was invariant.

Fuel Temperature. Increasing the fuel temperature resulted in a decrease in  $c^*$  efficiency suggesting that the element is experiencing reactive stream separation. Over the range in fuel temperature from 70 to 250°F the  $c^*$  efficiency decreased by 8 %.

Oxidizer Temperature. The oxidizer temperature was varied from about 50 to 110°F. Over this range no variation in performance was observed.

Chamber Length. The chamber length was varied from 4 to 10 inches and  $c^*$  performance changed by about 1%. These results suggest that the performance is mixing limited.

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## STABILITY

During all tests stability was monitored using a Kistler transducer placed near the injector face. No bombing was attempted so that any instabilities encountered were either triggered by the engine start-up characteristics, spontaneous, or from a pop caused by the impingement of hypergolic propellants.

### Like-Doublet Injectors

The combustion characteristics for the like-doublet injectors were in every case stable. Combustion was extremely smooth and no pops were observed on the traces.

### Unlike-Triplet Injector

Some instability occurred on practically every test using the triplet injector. Low frequency (~300 cps) oscillations would appear immediately after start-up and in most cases damp out, within 0.5 sec. In some cases the instability continued throughout the test. In other instances after the initial instability had damped out, steady-state combustion would continue for about 1.0 sec then spontaneously the low frequency oscillations would reappear. Study of the operating conditions suggest that the instability is not related to the operating conditions but must be inherent in the overall manifold/injector element design. The instability did not appear to be triggered by a pop and variation in peak-to-peak chamber pressure was 10 to 30 psi.

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## CONCLUSIONS

Based on the results presented above, the following conclusions can be made:

1. Like-doublet injectors can be designed for avoidance of blowapart even at MMH-injection temperatures of 250°F.
2. Both like-doublet and triplet elements under some design conditions are sensitive to fuel temperature which causes reactive stream separation.
3. Oxidizer temperatures up to 100°F do not affect  $c^*$  efficiency.
4. Mixing characteristics are more sensitive to fuel temperature than oxidizer temperature at temperatures up to 100°F.
5. Comparison of scale and full-scale results suggests that inter-element mixing substantially reduces the performance loss due to reactive stream separation.
6. In most cases mixture ratio and chamber pressure do not affect  $c^*$  efficiency.
7. The  $c^*$  efficiency appears to be mixing limited.
8. Based on schedule tests, a substantial performance improvement (relative to L/D #1) was achieved with the optimum element. This improvement on a full-scale injector will be considerably less due to inter-element mixing. A 1 - 2 percent performance improvement for the full scale optimum configuration is expected.